A DOUBLE PERFUSION-PUMP.

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THE heart-lung preparation of Starling and his co-workers has provided a means, extensively used, of studying the functions of the mammalian heart when working against an artificial and adjustable peripheral resistance, which replaces the natural resistance of the systemic vascular system. Many schemes have been devised and used, on the other hand, in which the blood has been perfused through the living vessels of an organ or part of the body by use of an artificial pump. Our original object in devising the pump here described was to produce an adjustable mechanism which could be used to replace the heart, and to carry on both major and minor circulations of the whole body. This would obviously require two synchronously working pumps. Since the two pumps would be working against widely different resistances it was further important that their throws should be rapidly and independently adjustable while running, so as to maintain such equality of output on the two sides as would prevent accumulation of blood on one side of the system, with deleterious back-pressure on the capillaries of the lungs or of the rest of the body, as the case might be. If the pumps and tubular connections were perfectly non-distensible, it should, theoretically, be possible to dispense with such adjustment; the two pumps being set to deliver equal amounts per stroke, they should continue to do this whatever changes occurred in the relation of the pressures they had to overcome. In practice, however, it would be very difficult to make a system of such ideal rigidity. The apparatus which we designed, in which diaphragm-pumps were used, certainly would not have it. The arrangement was accordingly devised which enabled the throw of either pump lever to be increased or decreased quickly and adjusted with delicacy. Embley and Martin (This *Journal*, 32. p. 147. 1905) used two rubber bulb-syringes, compressed by adjustable rotating cams, for a similar purpose. Our apparatus should give greater rapidity and precision of control, but the principle is the same.

DESCRIPTION OF THE DOUBLE PERFUSION-PUMP.

The pump is shown in plan in Fig. 1 and in elevation in Fig. 2. Both drawings are sectional where this method of presentation has been considered necessary to demonstrate the relations of the working parts. The

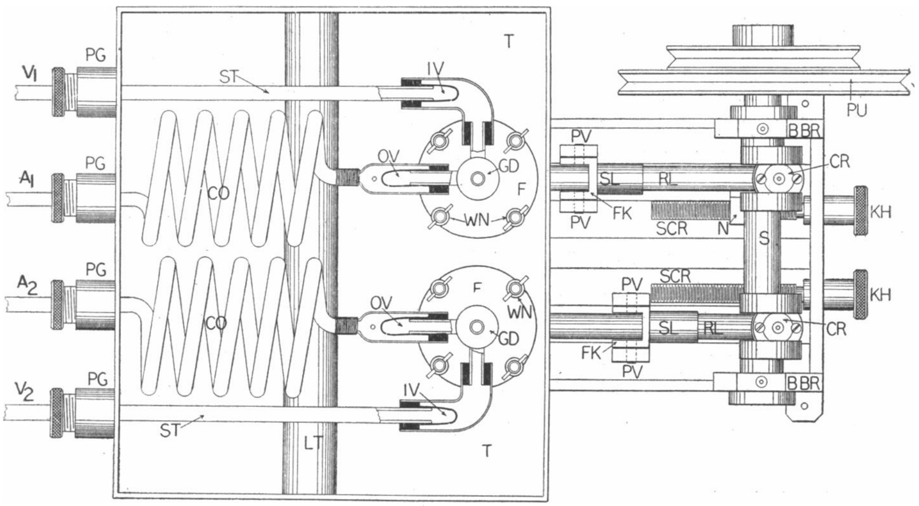
V1
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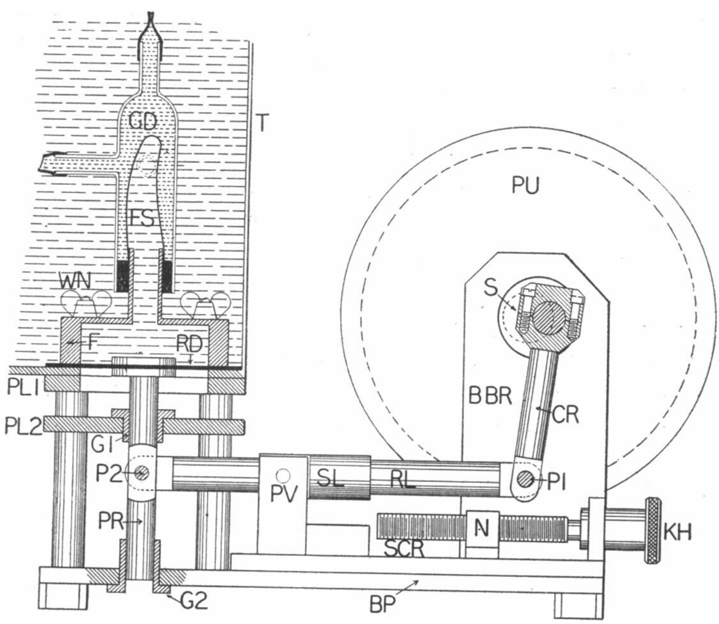
Fig. 1.


GD
T
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PL1
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PU
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RL
P1
PV
N
SCR
KH
BP

Fig. 2.

whole apparatus is not shown in Fig. 2. It consists of base plate, *BP*, carrying at one end the crankshaft bearing-bracket, *BBR*, at the other end, a double platform *PL* 1 and *PL* 2, supported on four pillars, of which two only can be seen. To the upper platform is attached one end of a tank, *T*. The other end is supported by adjustable legs (not shown).

The crankshaft is driven by a pulley, *PU*, and operates two connecting rods, *CR* (only one shown in elevation), by means of separate cranks. The lower end of each connecting rod is shaped to fit in a slot cut in the hinder end of a rocking lever, *RL*, and is kept in position by a pin, *P* 1. The forward end of the lever is slotted to form a fork embracing a flattened section of the pump rod, *PR*, to which it is pinned by the pin, *P* 2.

The position of the fulcrum of the lever can be adjusted by the following device, either while the pump is in motion or when it is stationary. A gunmetal sleeve, *SL*, which is free to slide on the rocking lever, carries at its forward end a square fork, *FK*, lying between two cheek pieces to which it is pivoted at *PV*. This pivot is the actual fulcrum of the lever. The cheek pieces are attached below to a slide which runs in a dovetailed guide on the base plate. The position of the slide is adjusted by means of a screw, *SCR* (which can be rotated by its knurled head, *KH*), and the nut, *N*, attached to the slide. When the slide is in its most forward position, the pivot, *PV*, comes exactly opposite the pin, *P* 2, and no motion is imparted to the pump rod. When the slide is screwed back as far as possible, the arms of the lever are approximately of equal length and a stroke of about $\frac{5}{8}$ in. is given to the pump rod. The pump rod, *PR*, is vertical and runs in guides, *G* 1 and *G* 2, carried respectively by the lower platform, *PL* 2, and the base plate. A rubber diaphragm, *RD*, is attached to its upper end by means of two brass plates, one fixed to the pump rod and the other screwed to the first through the rubber. A circular hole, 2 in. in diameter, cut in the upper platform and a corresponding hole in the bottom of the tank allow the central portion of the rubber diaphragm to move downward with the pump rod when it is depressed. The edge of the diaphragm is clamped between the large end of a thick-walled brass funnel, *F*, and the bottom of the tank by four wing nuts, *WN*, working on bolts which pass through the wall of the funnel, the bottom of the tank and the upper platform, their heads being fixed to the latter.

Round the tube of the funnel is fixed the open end of a rubber finger stall, *FS*, and surrounding it, held in position on the tube of the funnel by a rubber bung, is a glass dome, *GD*. The funnel and finger stall are filled with water, and the glass dome outside the finger stall with blood or other perfusion fluid. When the diaphragm rises, water is forced into the finger stall, which expands and drives the blood out of the glass dome. When the diaphragm falls, the reverse process occurs. In order to provide for the passage in each direction of the blood, two tubes are blown to the side of the dome at right angles to one another and to the long axis of the dome. One of these is connected, as shown in section in Fig. 1, to the inlet valve, *IV*, and the other, to the outlet valve, *OV*. The valves themselves are rubber caps each with a transverse cut near its closed end. The inlet valve is slipped over the end of a straight glass tube, *ST*, which passes through the tank and out of it by way of a packed gland, *PG*, which forms a water-tight joint between the tube and the tank. The valve-chamber is a short section of wide glass tube bent at a right angle and fixed with rubber bungs on the one hand to the straight tube, and on the other to one of the side tubes of the dome. The outlet valve is slipped over the other side tube; it is enclosed in a chamber with one wide end attached by a rubber bung to the side tube and the other end narrow. The narrow end is connected by rubber tubing with one end of a coil of glass tubing, *CO*. The coil at its other end passes into a straight tube which emerges from the tank by way of a packed gland. A small vertical branch tube comes off each of the outlet valve-chambers, and vertical tubes are blown on to the top of each dome. These tubes are used in filling the domes, and to allow air to escape. When the apparatus is in use, they are closed by short lengths of rubber tubing and clips.

Though the figure shows the glass warming-coil attached to the outlet (arterial) side of each pump, it will be obvious that it could equally well be attached to the inflow side, and the straight tube to the outflow; and this arrangement was, in fact, used in the perfusions actually carried out.

The tank is filled with water, which is kept at the desired temperature by a long narrow electric glow lamp housed in a brass tube, *LT*, passing across the tank near its bottom and soldered into holes in the sides. This lamp can be slid in and out of the tube by hand for rough adjustment of the temperature, or can be connected with a thermostat working a magnetic relay for finer control.

Use of the Pump.

The pump has not yet been used for its original purpose of producing a complete circulation of the heartless animal. It has been used, however, with success for experiments in which the hind quarters of a cat or dog were perfused by one pump and the lungs by the other, defibrinated blood being used. Open venous reservoirs were used into which the blood from the abdominal cava and the left auricle respectively discharged, and from each of which it was sucked into the alternative pump, from "systemic" reservoir into "pulmonary" pump and *vice versa*. When the throws of the two pumps are adjusted to the proper relation, the level of the blood is stationary in both venous reservoirs. Any change in the relation of the peripheral resistances, usually occasioned by a rise or fall of the systemic resistance, causes one venous reservoir to fill at the expense of the other, and necessitates a new adjustment of the relation between the throws of the pumps if a new equilibrium is to be produced. A very satisfactory perfusion can be maintained in this way for many hours.

The details of procedure in setting up an experiment of this kind may be given. The quantity of blood required to fill the apparatus shown in Figs. 1 and 2, including the spaces between finger stalls and glass domes, the valve-chambers, the glass coils and the tubes is about 50 c.c. Another 50 c.c. at least is required to provide a small reserve in the venous reservoirs and fill the connecting tubes. At least 100 c.c. of blood, therefore, should be available to fill the system before a perfusion can be begun, and if any but a very small organ is perfused more will be required. It is accordingly easy to perfuse a dog's hind limbs and lungs with its own blood, but for perfusion of a cat's limbs and lungs it is necessary to use one cat to provide the first charge of blood for the apparatus and a second to provide a further quantity of blood as well as the organs for perfusion. The animals were always bled out under anæsthesia with ether, cats from a cannula tied into the abdominal aorta, dogs from a cannula in a carotid artery. The blood was whipped with an indiarubber brush as it was received in a basin, and filtered through muslin, and then through a plug of washed cotton wool. By the time that the bleeding was completed, of the animal which was to furnish the organs for perfusion, an assistant had filled the apparatus with the earlier part of the defibrinated and filtered blood. The next step was to prepare the lungs for perfusion. The animal being killed, the chest was widely opened, and a bulb cannula, with inlet tube and outlet nozzle and side tubes for insertion of a thermometer and for connection with a manometer, was tied by its nozzle into the main pulmonary artery, which had been clamped as near as possible to its bifurcation, opened and washed out with saline. A strong ligature was then tied in the auriculo-ventricular groove, if this had not been done previously, and the ventricles were usually cut away. A wide cannula was tied through a slit in the apex into the appendix of the left auricle. A respiratory cannula was tied into the trachea, and this with the attached lungs, heart and cannulæ was removed from the body, and transferred to the apparatus. The arterial cannula being carefully filled with blood was then connected by rubber pressure-tubing with one of the arterial outlets of the pump (say A_1 in Fig. 1). The other arterial outlet (A_2) would be connected for the time directly by blood-filled rubber tubing with V_1. The cannula from the left auricle was connected by a rubber tube so as to discharge into the venous reservoir from which, during action of the pump, the blood was sucked by V_2. The connections all being safely made, to the exclusion of bubbles, the artificial respiration-pump was started, and then clips were removed and the circulation-pump set in motion. During circulation of the first 50 c.c. or so through the lungs, the outflowing blood from the left auricle was caught in a dish, whipped and re-filtered, pre-filtered blood from the reserve being added to the reservoir as required during this process. Finally all the blood available was returned to the system, in which it now circulated into the pump through V_2, out through A_2, directly from this to V_1, out through A_1 to the pulmonary artery, through the lungs, and from the left auricle back to the reservoir feeding V_2.

While the defibrinated blood was thus being circulated through the lungs, cannulæ were being inserted for the systemic perfusion, either into the lower ends of the abdominal aorta and vena cava, for perfusion of both hind limbs, or into the femoral artery and vein for perfusion of one leg. In either case, loss of blood through collateral channels had to be excluded by careful mass ligaturing. The hind quarters were then detached from the rest of the carcase and transferred to the table adjoining the perfusion-pump, which was now stopped while the attachments were completed. The arterial cannula was filled and attached, with exclusion of bubbles, to the pressure-tube leading from A_2, while the blood from the venous cannula was led by a rubber connection to discharge into the reservoir feeding V_1. The pump being started, the first portion of blood issuing from the limb-veins was again caught, whipped, re-filtered, and then returned to the reservoir. Connection was now made between the arterial cannulæ and the corresponding manometers and the strokes of the pumps so adjusted that the levels in the two reservoirs remained practically constant.

In our experience, as in that of other workers, the use of the lungs for oxygenation preserves the blood in a much more physiological condition than does an artificial oxygenator, such as that devised by Hooker and used by Burn and Dale. Not only is the potent vaso-constrictor effect of the freshly defibrinated or heparinised blood removed by the preliminary circulation through the lungs, but the moderate and more normal vascular tone of the systemic vessels thus produced is maintained during a long perfusion; the vessels long retain their reaction to constrictor and dilator drugs, and œdema of the organs is long postponed.

It will be obvious that, where a single pump only, with readily and accurately adjustable throw, is required for any physiological purpose, one pump of the type described above can be used. Such a unit, as made by C. F. Palmer, Ltd., is illustrated in Fig. 3. Obviously two or more of

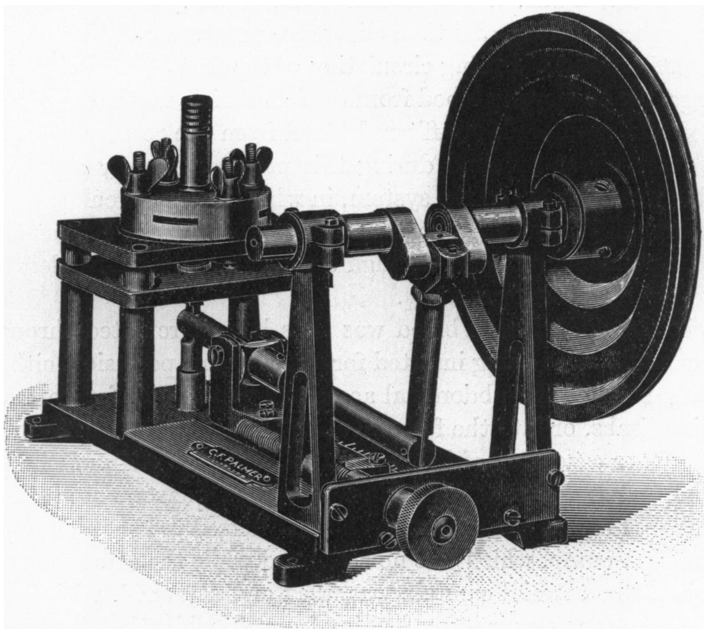

Fig. 3.

these could be arranged to drive from a common shaft. Similarly the thermostat bath, in which the pumps are immersed in the system above described, may for some purposes be omitted or replaced by one more suitable for the particular need. We are having one constructed at present in which the tubes from the pumps enter a chamber jacketed with warm water, in which a double perfusion of liver and lungs can be carried out without surface cooling of those organs. For the perfusion of the liver, as described by Dr Bodo and Mr Marks in a following paper, the use of the apparatus was further modified by using one pump to raise blood to an overflow reservoir, from which the portal vein was perfused under constant hydrostatic pressure, while a pulsatile pressure was produced

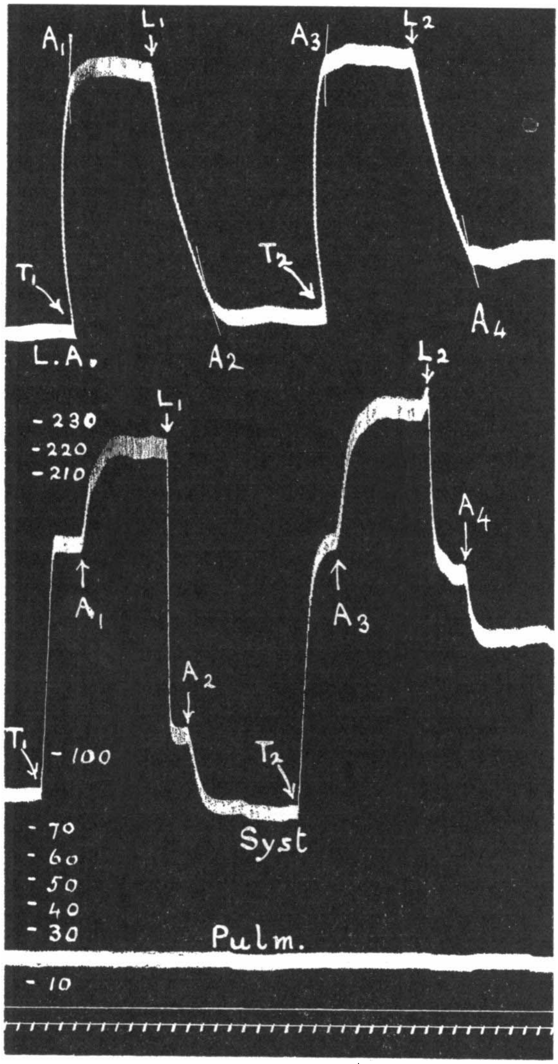

Fig. 4. Lines of record, from above downwards: Volume of fluid in "pulmonary" venous reservoir; "systemic" arterial pressure; "pulmonary" arterial pressure; pressure zero; time in 10 sec. intervals.

in the hepatic artery by use of the other pump. The apparatus can doubtless be adapted in other ways for other special purposes.

Fig. 4 shows a record of the pressures in the "pulmonary" and "systemic" arterial cannulæ in perfusion through an artificial scheme, the systemic and pulmonary resistances being represented by a high and a low resistance respectively on the two sides of the double circuit. The volume recorder, communicating with the air-space above the fluid in the "pulmonary" venous reservoir, equivalent to a stationary left auricle, shows (*LA* in Fig. 4) the balance of the circulation through the two widely different resistances produced by adjusting the relation of the two pump-strokes. A slight tightening, at T_1, of the clamp producing the "systemic" resistance causes a rise of systemic arterial pressure from about 80 to 180 mm., and an increase of the volume of fluid in the pulmonary venous reservoir, at the expense of that in the systemic reservoir. A small adjustment of the pump at A_1 restores the balance at the new relation of resistances, but the increase of stroke required to effect this causes the systemic pressure to rise further to about 220 mm. At L_1 the clamp producing the systemic resistance is slightly relaxed, producing a fall of systemic arterial pressure, and a loss of fluid from the pulmonary venous reservoir. To balance this loss, the stroke of the systemic pump must again be reduced at A_2, producing a further fall in the systemic pressure. The whole cycle is then repeated at T_2, A_3, L_2 and A_4. It will be seen that the apparatus is made to produce, after a delay allowing the disturbance of equilibrium to become manifest, that adjustment of the work done by the pump to the resistance encountered by the outflow, which is necessary to restore equality of output from both pumps. This is, of course, the adjustment which the living ventricle makes immediately and with great precision, and failing which any increase of systemic resistance would produce rapid dilatation of the left auricle, and back pressure on the lungs. Apart from its use in carrying out experimental perfusions, and studying the effects of vascular reactions uncomplicated by this automatic adjustment of the living heart, the apparatus might have some value for purposes of demonstration, enabling the nature of this adjustment, and its necessity, to be shown with great clearness and precision.

Summary.

A double perfusion-pump is described, by which any part of the systemic vascular system and the pulmonary system may be perfused in continuity, and the outputs adjusted in relation to the varying resistances while the pump is in motion.